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Patentanmeldung Nr. | Patent application No. | Demande de brevet n°

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System, method and joint monitoring sensor for laser spot welding

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System, method and joint monitoring sensor for laser spot welding

ABSTRACT

In present-day industry, and in particular in the area of microelectronics packaging and assembly, there is a strong demand for highly reliable, miniature joints of thin copper parts. Laser-welding could be the perfect solution for making such joints if this process would not be highly sensitive to various parameters, such as: reflectivity of the copper work-piece, gap between the product parts to be welded, and laser-power density. The robustness of the process is limited further because two important product properties (reflectivity and heat-conductivity) change strongly during welding.

An investigation has been performed to increase the robustness by means of real-time feedback control based on several parameters which are monitored simultaneously during the process. It will be shown how this drastically decreases the influence of the above-mentioned variations in the case of so-called heat-conduction welds. The control algorithm has been based on an approximate model of the (non-linear) welding process. In addition it will be shown how adaptive feedforward control is required in order to cope with the limited response time of the system. Finally, some remarks will be made on experiences with quality monitoring and iterative learning control.

Keywords: laser-welding, micro-spot-welding, copper-welding, process-control

1. INTRODUCTION

Laser micro spot welding is a joining technology, using a laser beam to heat the work piece parts to be joined. The laser beam is focussed onto a tiny spot in the range of some tens up to some hundreds of microns, thereby reaching very high power densities in the laser spot, capable of realizing a melt in and a fusion of the work piece materials in a few or even fractions of a millisecond. The combination of small welding spots and the short process times lead to a small heat effected zone, which makes this technique an ideal candidate for small delicate parts, which require well-controlled physical dimensions or geometrical stability.

Development of a robust process for novel applications needs experts on this technology to prepare the processes and to obtain stable operation with a high up-time for the production equipment. The state of the art technology uses feed-forward controlled laser output power. A certain power profile as a function of time and/or position on the work piece is used in specific cases to improve performance.

In order to make laser technology easier accepted in the industry, there is a drive to introduce self tuning characteristics to the laser processing equipment, making the system more robust to changing parameters in the process. Introduction of feedback techniques based on information from the process is necessary to achieve this goal. Some form of process monitoring has to be introduced and the process signals have to be analyzed and related to the actual conditions of the process at that moment. Having feedback control in place, opens up new options as it will allow the processing of materials which show a very narrow processing window or even do not have a stable process at all. Laser micro spot welding of bare copper using Nd:YAG laser sources is such a process. Because copper is an important material in the electronics industry, considerable effort has been invested in the development of laser spot

welding technology using Nd:YAG sources with feedback control, resulting in stable operating processes.

2. PROBLEM DEFINITION

Only a limited number of applications are running at the moment using laser (micro) spot welding on copper with the commonly used Nd:YAG laser sources. Two main reasons can be identified for this situation:

1 The process has a few parameters which show significant variations from work piece to work piece.

The laser power of the beam is only partly absorbed by the surface of the work piece. The absorption coefficient for the 1064 nm radiation from the Nd:YAG source by pure copper is about 5%. Measurements have shown that variations up to 10% can be expected upon this figure, depending on the storage and treatment of the material.

Parts to be joined have to be brought together. The remaining distance between the parts is always subjected to some variation, affecting the heat diffusion through the structure and in the end the (start of the) fusion process.

2 The process behavior changes dramatically during phase changes.

Copper has a high heat conductivity, which calls for short process times, thus high laser power, to keep the energy input and the heat affected zone small. The absorption coefficient of copper is depending on temperature, and changes abruptly when going through the solid–liquid phase change. A similar behavior is present in the thermal conductivity, however with an opposite sign. This means that at changing state, the absorption of laser radiation increases, while the thermal conductivity decreases, leading to a very fast increase of the local material temperature when the input laser power remains constant. Without taking precautions, the process runs very fast into evaporation of the copper at the center of the spot weld and soon after that into an uncontrollable key-hole welding regime.

A sudden increase of laser power absorption will also occur when the process runs into key-hole welding regime. The evaporated material pushes the liquid material aside, thus creating a dent and in the end a hole. This 'black' hole leads to almost full absorption of the laser beam energy.

The problems related tot he first group (absorption of laser energy) could be tackled by introducing a kind of pre-processing to the work piece surface leading to a more defined absorption for Nd:YAG (laser structuring, blackening with ink), or by selecting a laser source with a shorter wavelength, leading to a higher and more reproducible absorption coefficient (frequency doubled or tripled Nd:YAG). The effects of group two are purely defined by the material and process behavior as such and have to be accepted. Although solving the laser in-coupling problem will be a very important step in getting the process under control, it will not lift all problems for laser spot welding of copper parts.

3. METHODOLOGY

The approach followed to tackle the problem, is to introduce a feedback controlled laser power source, on basis of measured process parameters. The major drive for this choice is the consideration that this is a way to control process variations originating from work piece variations, material properties as well as process conditions.

As stated in the previous chapter, the problems related to laser spot welding of copper are caused by a number of different parameters and process conditions. Based on the presented problem definition, we can extract the following list of important parameters and process conditions which are of crucial importance to the process behavior.

Absorption coefficient of the work piece surface for the laser light
Heat diffusion through the work piece structure
Distance between the parts to be welded
Solid-liquid phase change (changing physical properties)
Liquid-vapour phase change (condition for key-hole operation)

It is obvious that a number of sensors are needed to detect the behavior/presence of this set of process parameters and process conditions. This set of sensor signals is used to keep the process under control, by measuring the behavior of process parameters on the one hand (energy absorption and surface temperature) and process conditions on the other hand (solid-liquid phase change, liquid-vapour phase change).

4. PROCESS & MONITORING

4.1 Process behavior

Laser (micro) spot welding is a joining technology, which is frequently used for miniature welds on small products. The typical characteristic of this joining technology is that the laser beam remains focussed on the same spot during processing. The processing times are short, in the order of 0.5 – 20 ms.

Several different welding types are used in industry, among which the standing edge weld, the overlap fillet weld and the overlap penetration weld are the most important (Figure 1).

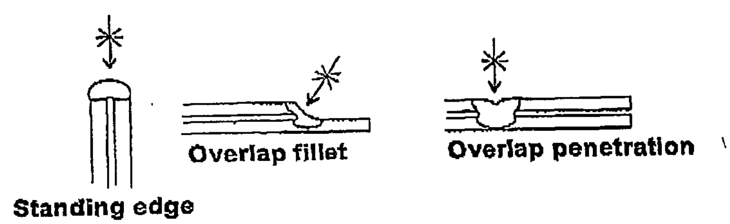

Figure 1 Laser spot welding geometries

The overlap penetration weld is the most critical geometry because the distribution of the laser energy over the work piece is heavily influenced by the interface between the two metal parts. Figure 2 shows a kind of time resolved process condition overview of the (micro) spot welding process for the overlap penetration geometry.

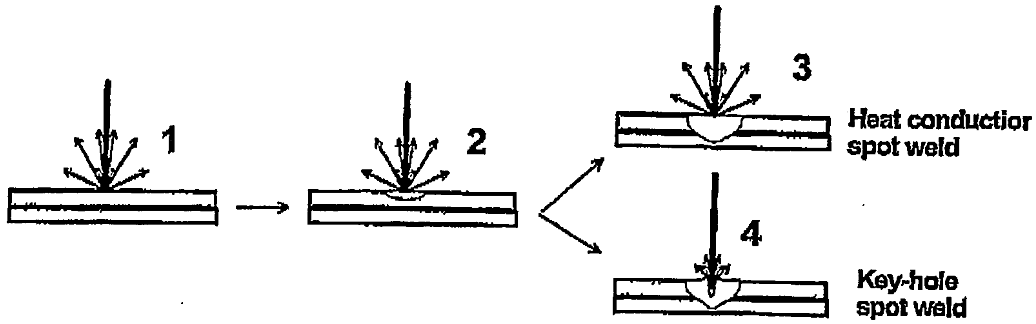

Figure 2 Time resolved process phases for micro spot welding

Phase 1 is the pre-melting phase. For most materials the absorption increases with temperature, so the process more or less accelerates during heating. For copper, the transition from solid to liquid introduces a steep change in process behavior. The energy absorption increases while the heat distribution decreases, leading to a rapid temperature rise when going into liquid phase (with constant input power). Figure 3 and Figure 4 show the behavior of laser power absorption and heat diffusion as a function of temperature for stainless steel and for copper, to indicate the major difference [1],[2]. The process runs rather stable on stainless steel products due to the physical behavior of that material. The absorption coefficient for the 1064 nm light of the Nd:YAG lasers is quite high and the thermal conductivity is low compared to other metals: The energy is accepted easily, while it remains more or less locally concentrated.

In contrast to stainless steel, copper shows a step wise change of both the thermal conductivity and the energy absorption at the solid-liquid phase change. Both effects have an accelerating influence on each other, leading to a kind of avalanche behavior on the local temperature of the material. Unless precautions are taken by lowering the laser power significantly, the center part of the sot will soon go into the key hole operation, often leading to liquid material exploding from the weld spot.

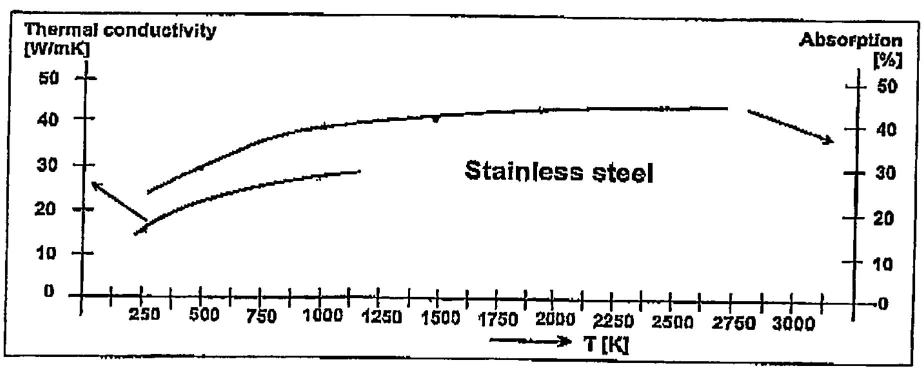

Figure 3 Thermal conductivity and absorption properties for stainless steel

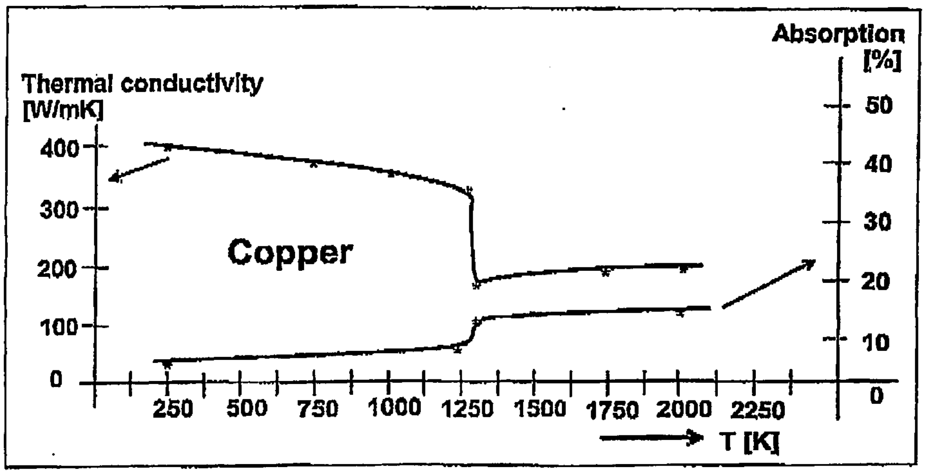

Figure 4 Thermal conductivity and absorption properties for Copper

Phase 2 is the melting phase, where the top material within the spot area is initially partly solid and partly liquid, while expanding to completely liquid at the end.

Phase 3 indicates the accomplished heat conduction weld. There is hardly any vaporization, leaving the surface more or less undistorted and flat.

Phase 4 indicates the situation in case of key-hole spot welding. The recoil pressure of the vaporized material pushes the liquid aside, caching the laser beam.

As indicated in the aforementioned overview of process phases, the absorption coefficient changes from phase to phase. Depending on the history of the copper material, the initial absorption coefficient can vary. Reducing the laser power immediately at the moment of melting is important to keep the process in stable operation. This moment is however depending on the amount of power absorption during the initial phase and even a 10% variation (which can be expected from normal oxidation) can be sufficient to cause stability problems. Problems can be made much smaller by improving and securing the absorption of the 'initial' material by means of a pre-treatment like oxidizing, etching, sandblasting or coating. As soon as melting occurs, the effects of the pre-treatment will be gone.

When the process goes into key-hole operation, a second change in absorption will start, taking the laser absorption up to almost 100 % in case of deep key-hole processing.

Introducing a pre-treatment to the material will give a better defined absorption during the in-coupling phase. Once molten, the disturbing effects of other process parameters like the gap between the parts are still acting on the process. The technology relies on the introduction of real-time feedback control techniques to handle the initial absorption variations as well as other process parameter variations like gap variation, affecting the heat diffusion through the structure. Figure 5 shows a representation of the absorption variation when the spot welding process runs through the sequential phases. The figure indicates the effect of the initial absorption on the process which follows.

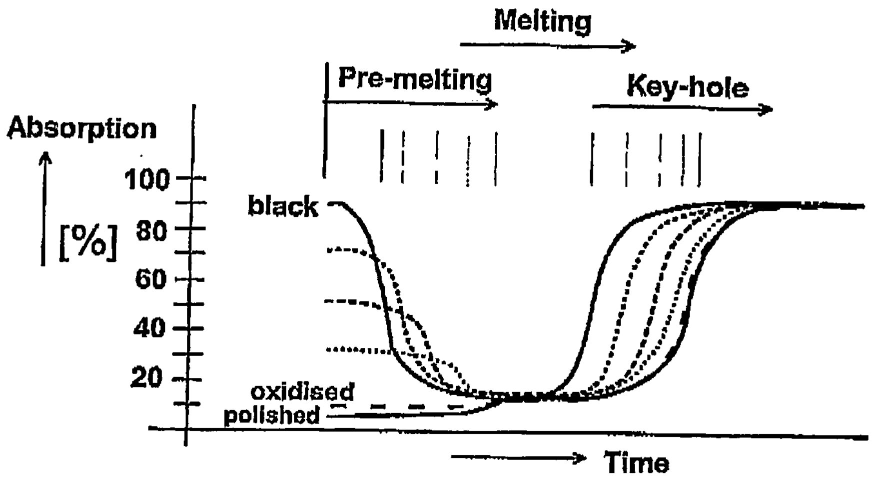

Figure 5 Absorption of laser energy over time, depending on the actual process phase

It is evident that the exact time instants of the critical phase changes vary and this is where the feed back control technique will help to align the laser source output to the evolving process.

Heat conductive welding on copper has been realized using feed-forward operation and by limiting the range of process disturbance by initial absorption variation. This process uses a relatively large spot size compared to the work piece thickness. Using the same weld type for the work, gives the option to compare the performance of the feed-back controlled process directly with the feed-forward operated process and establish in that way an opinion about the performance improvement with feed-back operated spot welding. The geometries used for the experiments and performance verification involved combinations of copper sheets of 100 and 50 micron thick.

4.2. Process monitoring

For effective process monitoring aiming for process control, it is vital to implement sensors that detect information which is linked to the critical process phenomenon mentioned in the previous paragraph. The next table presents the identified important process parameters and process conditions to detect and the related sensing system used on the set-up

Process parameter or process condition to be measured or detected	**Related physical property or properties**	**Implemented sensor**
Absorption coefficient of the work piece	Laser power to the work piece Reflected laser power from the work piece	Germanium photo diode Germanium photo diode
Heat diffusion through the work piece, Surface temperature. Distance between the parts to be welded	Infra-red emission from the surface	InGaAs photo diode
Solid-liquid phase change (changing physical properties)	Reflected laser power form the work piece Infra-red emission from the surface	Germanium photo diode InGaAs photo diode
Liquid-vapour phase change (condition for key-hole operation)	Optical emission from vapour	Silicon photo diode

Absorption coefficient of work piece:
On-line measurement of the absorption coefficient of the work piece surface can not be done with high accuracy. The practical set-up does not permit the measurement all reflected laser power. As shown in Figure 6, only the reflected power which returns into the aperture of the optical system is measured. The input laser power is measured reliably with a sensor behind the first mirror, detecting a fixed fraction of the incoming laser power, passing this mirror. Only an indicative value can be extracted when monitoring the reflected laser signal over a certain period.

Heat diffusion through the structure, Surface temperature.
The applied laser energy will diffuse through the work piece structure, resulting in a certain temperature gradient profile in the work piece structure. This profile is hardly accessible by on-line measurements, but some information about the heat distribution can be extracted by looking at the dynamic response of the surface temperature. Small variations in heat diffusion can not be resolved, however the actual existence of metallic contact between the two copper sheets can be detected. Verification tests have shown that the used InGaAs sensor in our set-up can detect emissions from the surface down to a temperature levels of about 600 °C.

Solid-liquid phase change
Two sensors in the set-up have been used to detect the crucial solid-liquid phase change. As soon as the surface within the weld spot changes state, the reflection properties of the material changes instantly. The speculair reflection from the surface decreases at the expense of the diffuse reflection. This can be recognized form the implemented laser power reflection sensor, showing a rapid decrease of the signal at the moment of melting.
There is a fixed relation between the surface temperature and the moment of melting for each

specific material. This means that also the infra-red emission can be used for tracing the melting event. This option is used for the implemented control module.

Liquid-vapour phase change

The most straight forward method of detecting vapour formation is the detection of the optical emission from the evaporated cloud above the weld spot. This has been done by coaxially as well as by means of an off-axis sensor. The advantage of the off-axis method is that this measurement can be de-coupled from the surface emission much easier compared to the coaxially implemented sensor. The off-axis sensor has been used in our control loop.

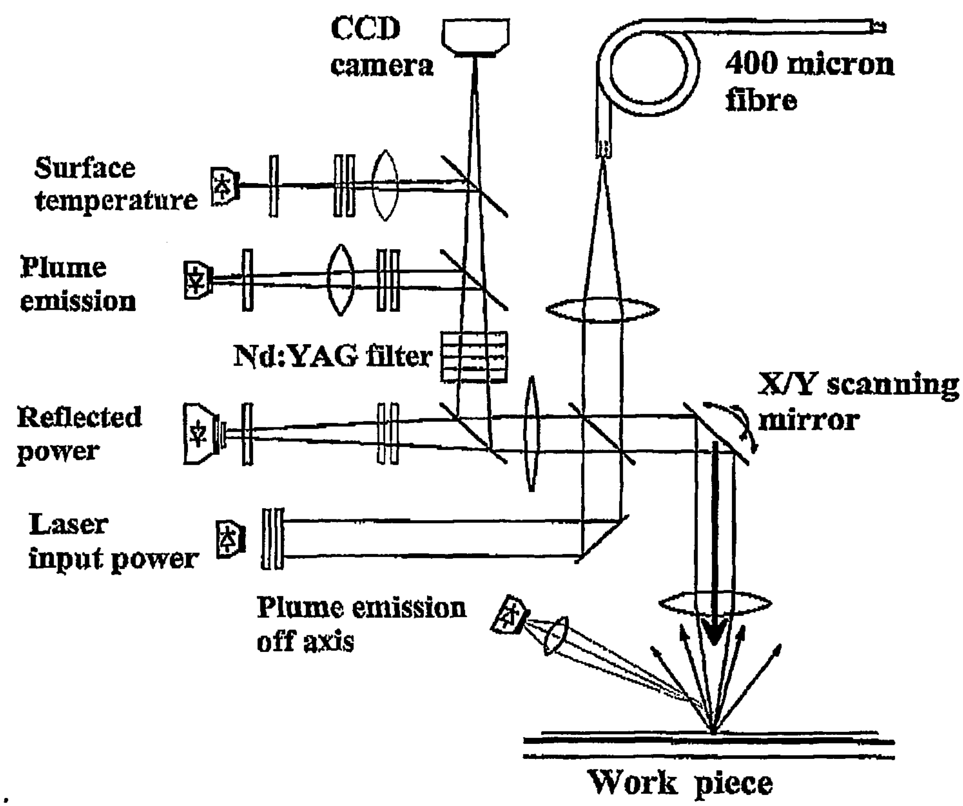

Figure 6 Implementation of sensors on spot welding set-up

Besides the optical sensors mentioned above, also other sensors have been tested and evaluated. These sensors showed however to be less favorable for reasons of complex signal processing (microphone) or signal consistency (eddy current detection of weld pool penetration).

A CCD camera gives a view on the welding spot and an be used in combination with machine vision techniques to align the position of the welding beam accurately on the work piece by moving the two scanner mirrors in the processing head.

5. SIGNAL PROCESSING

All sensors have local preamplifiers and the amplified signals are fed to a filter unit. This filter unit performs straight forward anti-aliasing filtering for all sensor signals. Besides that, the signals from the optical sensors are processed with a comb filter which suppresses the fundamental frequency and all higher harmonics of the switched mode power supply current to the flash lamps of the laser unit. The laser power modulation due to the chopper frequency is thus completely suppressed in the sensor signals and will not disturb the control loop. Hard-ware filtering is selected for this application as it is expected that the full processing performance of the controller is needed for the control action as such.
The controller hardware is in this case the **DAP5200a signal acquisition processor board** from Microstar Laboratories. This board provides 8 analogue input channels with two AD converters with 14 bit resolution and a sampling frequency up to 400 kHz (50 kHz per channel in case all used). Two analogue output channels are provided to drive actuators. In our case only one is used for the power set-point to the laser unit. The processing of the input data and generation of the output signal, runs on the onboard processor.

6. CONTROL STRATEGY

It has not been without reason that so much attention has been paid on the fact that the absorption coefficient of the material changes considerably throughout the spot welding action. When realizing a closed loop operation, this means that a similar variation in the loop gain in fact present. Loop gain variations as indicated in the previous chapter can not be handed satisfactorily by one single controller. For best performance, the controller has to adapted to the loop gain of the process in each phase. Based on this thought, the control strategy of Figure 1 has been put forward.

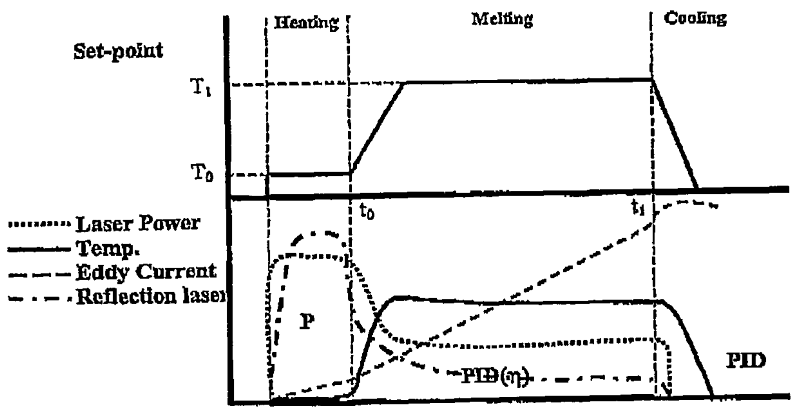

Figure 1 Basic control strategy for laser spot welding of copper sheets

Each of the three process phases 'Heating', 'Melting' and 'Cooling', has it's own controller settings.
The first hurdle to take is to come safely through the in-coupling phase. The material has to be heated from room temperature to a temperature just above melting temperature, without the process getting unstable due to the solid-liquid phase change difficulties described in chapter 4. This is achieved over the proportional controlled heating phase. As soon as the measured temperature exceeds a pre-set threshold value, the heating phase is accomplished

and the melting phase is started. This phase controls the laser power such that the measured surface temperature follows the set-point contour. The PI controller takes the temperature from just above melting up to the desired fusion temperature and keeps it there for a certain period. The third phase takes to temperature down according to a linear slope. For copper, this cooling curve is not very critical.

6.1. Controlling the welding process

A general scheme of the control scheme for the welding process is depicted below.

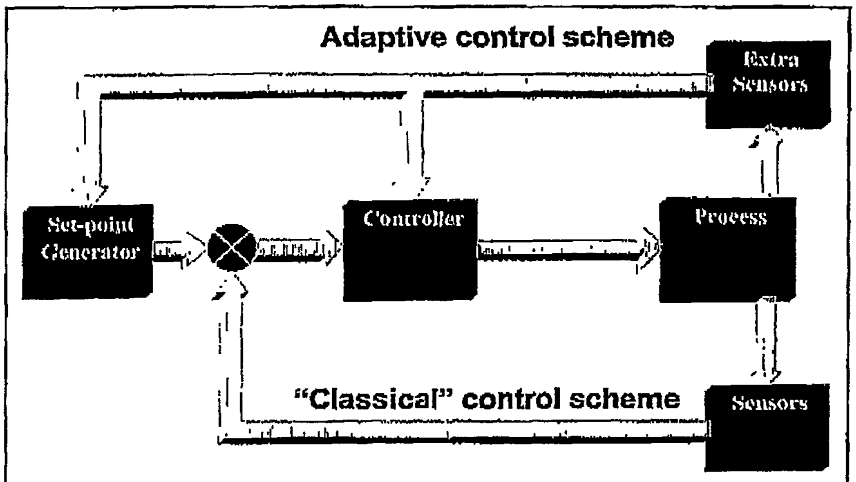

Figure 7General feedback and adaptive control scheme.

Three different controlling modes are applied for different purposes. Traditional feedback control (incl. common feed-forward support) has been used to enforce the welding process to track a given temperature trajectory during the welding phase of the process.
Besides that an adaptive controlling scheme has been employed to change from one controller to another when the process changes from one state (solid) to another (molten) and back again to the solid state. Finally, the feed-forward signal is adapted after every weld based on the occurred control error of every trial, with other words an Iterative Learning Controller.

6.1.1. Feedback Control

6.1.1.1. Model

The process consists of three subsystems: the laser equipment, the welding process and the temperature sensor.
The laser can be given an analogue input. This input between 0 - 6 V is a set-point for an internal laser controller that controls the laser power, corresponding to 0-6 kW laser power. The laser was previously investigated to have a first order behavior including a major delay. The welding process has been modeled based on step and sinus excitation data gathered during the molten phase of the welding process. The model found is a second order model with two zeros.
Finally the pyrometer used for the temperature measurement has been modeled or better said calibrated using a copper molten bath where a reference temperature signal was obtained

using a thermocouple temperature meter. The result of that investigation confirmed the theoretical model saying that the temperature is proportional to the fourth square root of the surface radiation of the weld spot. The total model can be described by:

$$H = \frac{\sqrt[4]{S}}{L} = e^{-t_d s} \frac{K}{\tau_L s+1} \frac{(\tau_{w1}s+1)(\tau_{w2}s+1)}{(\tau_{w3}s+1)(\tau_{w4}s+1)}.$$

with:
$K = 1.46$, $td = 196$ μs, $\tau_L = 0.137$ ms ($f_{wl} = 1162$ Hz), $\tau_{w1} = 1.061$ ms ($f_{w1} = 150$ Hz), $\tau_{w2} = 0.108$ ms ($f_{w2} = 1469$ Hz), $\tau_{w3} = 1.730$ ms ($f_{w3} = 92$ Hz), $\tau_{w4} = 0.335$ ms ($f_{w4} = 475$ Hz)

Below an example of the input and output signals of the process and the corresponding simulation signals are depicted.

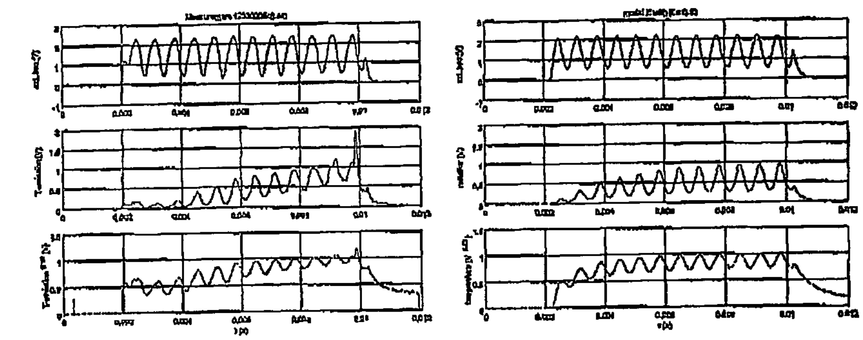

Figure 8 Measurement and model prediction to similar input

6.1.1.2. Feedback Controller Design

Due to the large model uncertainty, the feedback controller had to be designed. The controller is PI controller with a proportional part Kp of 3.3, and a frequency at 200Hz. That leads to a

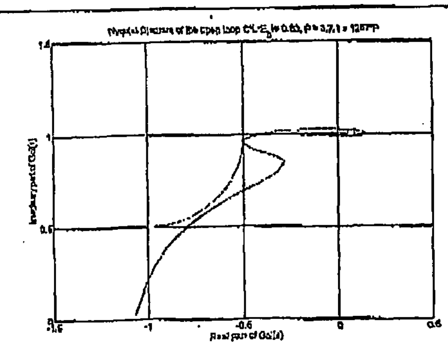

Figure 9 Nyquist diagram of the controlled process

controlled process with 260hz bandwidth. It is also obvious based on the Nyquist plot that the controlled process appear to gain margin more than 6dB and phase margin more than 45 degrees.

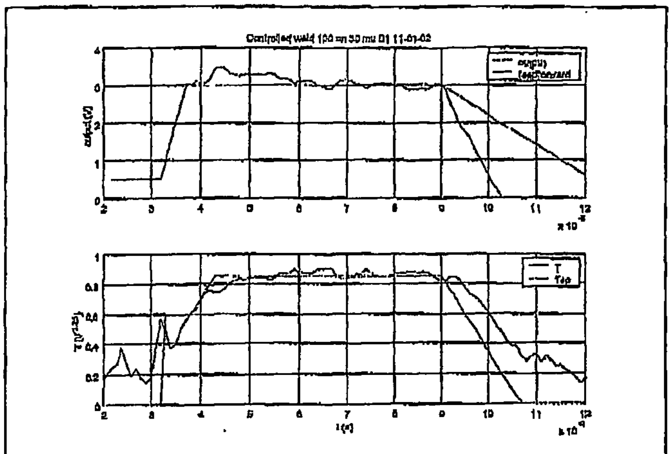

Figure 10 Example of controlled weld temperature and controller output

6.1.2. Testing of the basic controller

The implemented controller was tested on two kinds of penetration welds. The first one was a weld of two sheets of 100 μm thick copper; the second was a weld of a 100 μm thick sheet on a 50 μm thick copper foil. In the following figure an example is given of the temperature signal for a controlled weld of a 100 μm thick sheet on a 50μm thick foil.

Although most of the welds done with controlled system appeared to have a good and reproducible quality, a number of welds were much too small. Especially the performance on dirty (i.e. contaminated and rusty) sheets had to be improved. The basic controller has been extended to improve its performance. It was noticed that the length of the melting phase was of influence on the weld quality. The weld quality could be improved, if a sensor signal could be found from which the optimal melting phase length could be determined on-line. In the next section the extension of the feedback controller will be discussed.

6.2. Adaptive Control

6.2.1. Process Phases

The welding process has of course a direct relation to the thermal changes of the material to be welded. Therefore it changes drastically when the material passes from the solid state to the fluid state where the real fusion of the materials takes places. Therefore different process phases have been defined where on the one hand a different model has to be determined and on the other hand a different controller. In general we have defined the following phases of the process.
In the first phase, the laser power is kept constant until the material starts melting (therefore only a P-regulation is active). Next, the real controlling scheme is used to regulate the

process according to the melt surface temperature (in this phase a PID regulator is used. Finally we finish the weld at a certain moment (t_1) based on additional measurements (eddy current signal). The different phases will be described in more details in the next sections.

Pre-melting or heating phase

This phase involves the heating of the material till the melting phase starts. A *P-regulator* is employed here. The moment t_0 (see figure 4) will be determined from the reflected laser light signal, implying that the value T_0 of the set-point temperature will be adjusted following the value of the temperature at the moment t_0.

Melting Phase

The melting phase may be the most important phase, because during this phase the actual welding takes place. The aim during this phase is to keep the temperature constant till the moment the melt has reached a sufficient penetration depth.

As it is mentioned before, the length of this phase determines the quality and reproducibility of the weld. Therefore an smart regulation has been implemented to adaptively control the length of this phase.

During this phase the laser energy absorbed by the work-piece is monitored. The length of the melting is then in such a way regulated so that that energy is kept constant. The absorbed energy is calculated by the integration of the difference between the produced total laser light and the reflected laser light (which are by the way both measured). An example of signals of two welds where it is clear that the melting phase length is different is depicted below. When the reflection increases during the melting phase the length of that phase also increases so that the total surface between laser light and laser light reflection remains constant.

Post-melting or cooling phase.

In this phase the melting phase will be terminated with a certain cooling trajectory. For the specific application the cooling trajectory is not important for the quality of the joint. That 's why a simple PI controller is used to support the cooling phase. Nevertheless for other applications appear that the cooling temperature trajectory is of major importance.

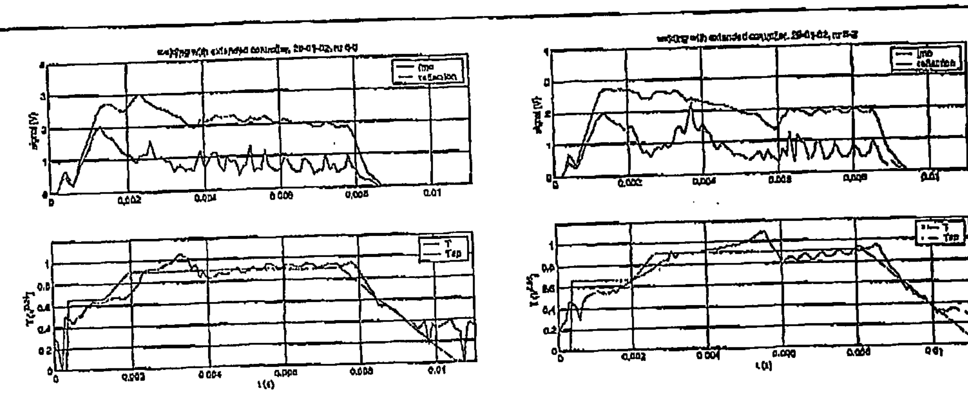

Figure 11 Phase regulation based on absorbed energy

The absorbed energy threshold was implemented in the controller to determine the length of the melting phase. With this feature the repeatability of the lower weld diameters improved

substantially. Especially in case of 100 µm thick dirty sheet on a 50 µm thick foil, the standard deviation of the lower diameter standard deviation of 15 % was achieved, instead of producing no welds beside good welds.

6.3. Iterative Learning Control

6.3.1. General

With the extended controller the reproducibility of the weld diameters has improved

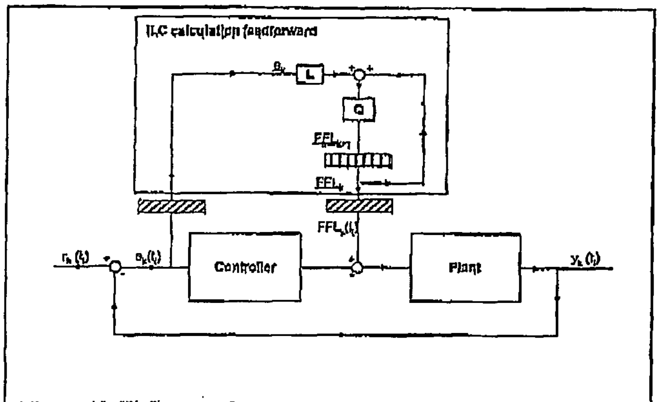

Figure 12 ILC general scheme

substantially, but the temperature still shows a large deviation from the reference at the beginning of the melting phase. iterative learning control (ILC) has been employed to get rid of the systematic disturbances that causes reproducible deviations of the temperature trajectory in reference to the set-point profile. In ILC, the error of the previous trail (in this case the previous weld) is used to update the feed-forward action off-line. If the systematic errors are larger than the random errors, the error will reduce. The applicability of ILC is studied by looking at the systematic and the random errors. Because this investigation shows that ILC can indeed be applied, an iterative learning controller is designed, implemented and tested.

6.4. Iterative Learning Control applicability

ILC can be a powerful tool if (for low frequencies) the size of the systematic errors is large in comparison to the size of the random error. Therefore, the repeatability of the error has been investigated. For four gap sizes (0, 20, 40 and 60 µm), two series of 20 or 19 welds have been made on clean and dirty copper respectively. An example of such a set of error signals is depicted in figure 13. For the clean sheets, the error is very reproducible, especially in the first 2 ms of the melting phase. When the errors of the welds with the four different gaps are compared, the reproducibility is smaller, but still visible. These and much more signals have been taken into account to determine the applicability of ILC.
In addition because the characteristics of the error of the clean sheets are still visible in the error of the dirty ones, the found feed-forward could also be used for the welding of dirty sheets, even when learning on dirty sheets shows to be impossible

ILC has been implemented and tested is different configurations. An example of the obtained results is depicted below, where the tracking behavior of the system is visualized before and after ILC.

The general observations regarding the ILC performance were as follows: From the control point of view, ILC performs good by means of better tracking performance. Nevertheless

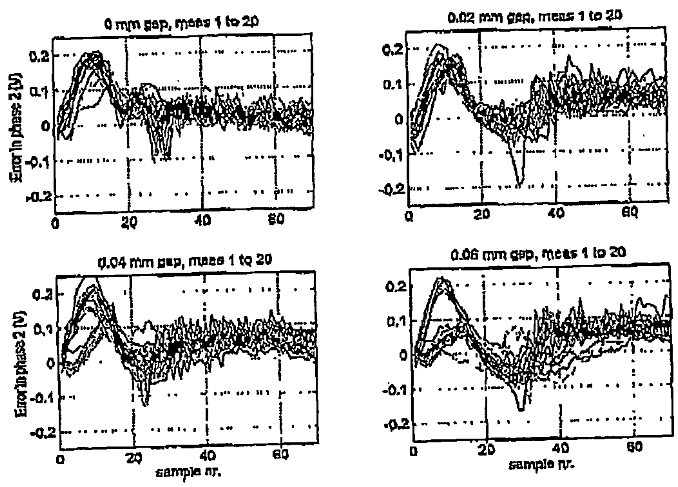

Figure 13 Error signals in melting phase, for welds on clean copper

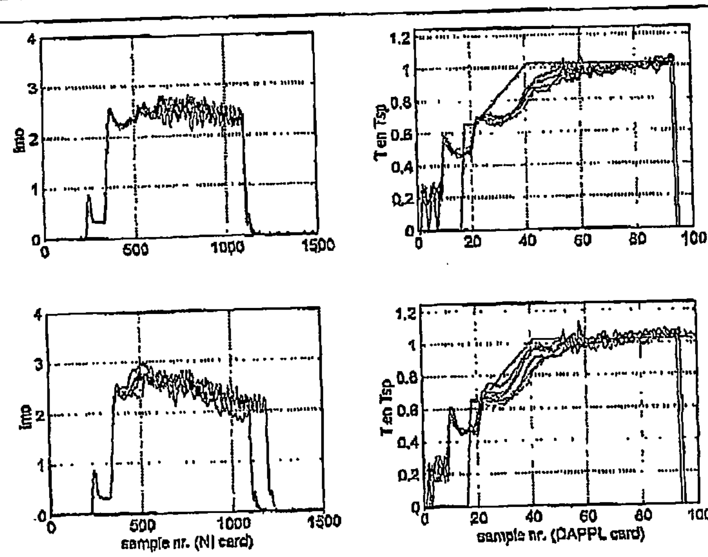

Figure 14 Learning experiment no gap, trials 1-5 and 6-10, learning starts at trial 6

when a gap is present between the copper sheets although the tracking performance is

improved the weld quality decreases. Regarding that issue we think that the set-point shape is not optimal tuned.

7. TESTS AND RESULTS

The bases for our verification tests was the comparison of state of the art heat feed-forward operated conduction spot welding using a certain fixed pulse shape, with the new feed-back controlled spot welding technique. The tests have been done on clean copper sheets as well as on copper sheets which were dirty. Spacers of 20, 40 and 60 micron thick have been used between the sheets to force a specific gap. The experiments showed that the actual size of the gap did not introduce much differentiation in the welding results. The fact that there is a gap is dominant. Table 1 shows the 'clean' version of the experiments of welding 100 onto 50 micron. Table 2 shows the results of similar experiments for dirty sheets. The third column presents the spread in weld diameter measured at the bottom of the joined sheets. This figure is a good measure for the reproducibility of the welding process. The fourth column simply gives the percentage of bad or failing welds.

Table 1 Performance verification on clean copper sheets 100 onto 50 micron

Gap	Strategy	Good Welds	Bad welds
[μm]		Spread DI(σ) [%]	Number [%]
0	Pulse shape	8	0
0-60	Pulse shape	24	28
0	Controlled	3	0
0-60	Controlled	4	0

Table 2 Performance verification on dirty copper sheets, 100 onto 50 micron

Gap	Strategy	Good Welds	Bad welds
(μm)		Spread DI(σ) %	Number %
0	Pulse shape	41	7
0-60	Pulse shape	38	47
0	Controlled	7	0
0-60	Controlled	8	5

Table 1 shows that the open loop operating process performs well in case there is no gap between the parts. The disturbing effect of the gap (heat distribution through the structure) is effectively handled by the feedback controlled process. A similar effect can be seen in case dirty copper is used, introducing an extra disturbance during pre-melting phase. A significant improvement of the joining technique is achieved using the controlled process, although the reproducibility with extra gap variations is not adequate anymore.

8. CONCLUSIONS

The above described methods can equally well be applied to materials other than copper, especially to materials which are relatively highly reflective and/or relatively highly heat-conductive.

9. ACKNOWLEDGEMENTS

10. REFERENCES

[1] Y.S. Touloukian, R.W. Powell, *Thermophysical properties of matter, Vol. 1 Thermal conductivity, Metallic Elements and alloys*, IFI/Plenum, USA, 1970

[2] Data from publications in magazines:
Kikuo Ujihara, Journal of applied physics, Volume 43 no 5, May 1972
Journal of Laser applications, No. 9 1977.

[3] A concept for Hydrodynamic Model of Keyhole Formation, Icaleo 1994 (641-650)
V.V. Semak, J.A. Hopkins, M.H.McKay, T.D. McKay
Center for laser Applications, The University of Tennessee Space Institute, Tullahoma.

[4] M. Steinbuch, *Iterative learning control*, course notes TU/e, 2001

The decay behavior of the temperature in the weld spot just after a laser spot welding process shows two clearly distinctive types of curves representing the presence or absence of a joint. Joint monitoring can be done by measuring the signal level in the time regime after switching off of the laser pulse, independent of the laser pulse energy.
Besides the differentiation between good welds and weld failures, the technique can also be used to monitor the evolving spot welding process. It can detect when the effective physical contact between the parts to be joined is established (change of heat transfer characteristics) and correct the process conditions during the process for optimum result, thus compensating for gap effects between the parts.

With the aid of this "Joint monitoring sensor" it is possible to detect the existence of a joint resulting from the laser spot welding process. The sensor cannot identify the gap size, but only the presence or absence of a joint as a result of the welding process. The sensor is a pyrometer type of temperature sensor, which detects the heat radiation in the band of 1350 nm -1700 nm.
The proven value this sensor are shown by the results of the welding experiments of the folded plates of Grid1 of a CRT electron gun and there is a significant temperature signal difference, between the situation with proper fusion and the ones without a joint being made. Fig. 1 below depicts the temperature decrease <u>just after the spot weld was made</u> for plates welding in the time range 5 ms - 14 ms. The actual spot welding process took place from 0 - 5.0 ms (active laser pulse).

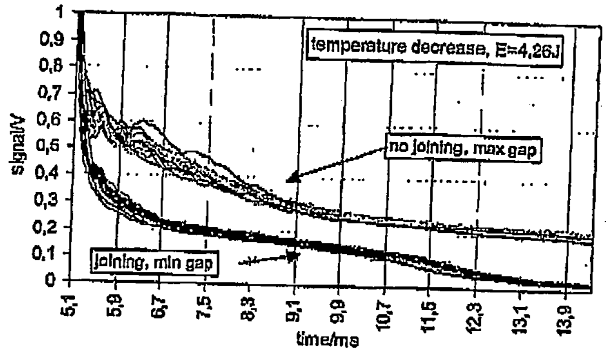

Fig. 1: Temperature decrease

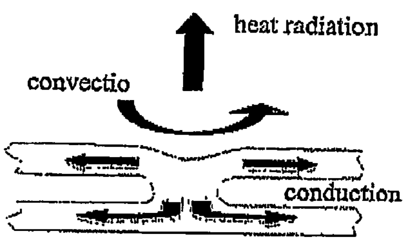

Fig. 2: Heat dissipation of welded plates

The reason for the different signal decreases are the different situations of heat distribution. If a good penetration is made, the joining between the two welded plates serves as "heat conduction bridge". With both plates connected, the heat can be dissipated faster, see Figure 2.

If no joint occurs, the major amount of energy is accumulated in the top plate and limited heat transfer takes place to the lower sheet, leading to a slower cooling slope.

Energy detection using the temperature curve.

Another important capability of the sensor is the detection of the energy during the welding process in relation to some reference energy setting which for example is available on some commercial weld monitoring sensors, like the 'ProWatcher' system of the LZH (Laser Zentrum Hannover), the 'LWM 900' of Precitec or the 'Weldcheck' of Rofin Sinar. In these systems, a reference is created with tolerance windows. These systems must be modified accordingly to detect also the energy level during the weld: using the proposed sensor the energy detection could be done by integrating the temperature signal in the first range (until attainment of the vapourisation phase).

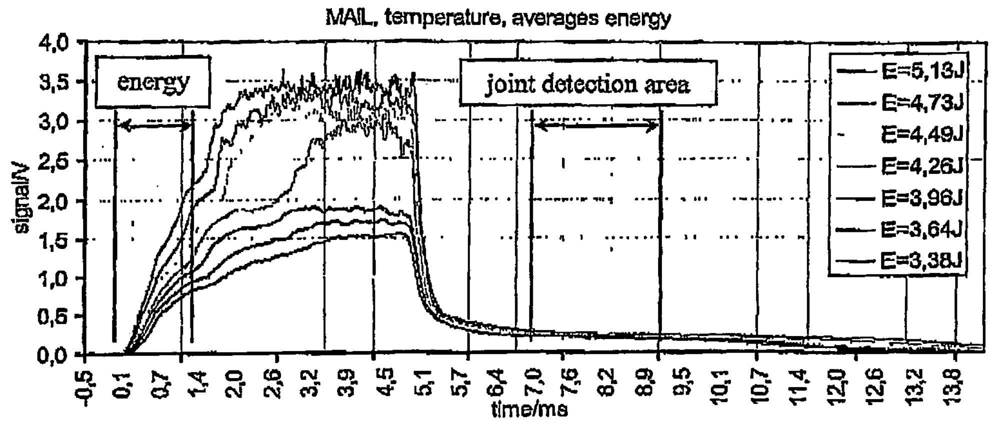

Fig. 3: Temperature curves depend on the energy

In the range marked 'energy' (Fig. 3) the energy value can be calculated. Here the measured temperature radiation is a value for the energy setting (for the same work piece geometry and absorption coefficient); in fact the absorbed energy by the work piece leading to a certain temperature level and directly associated thermal emission. The actual energy value, which is detected, will be compared to the settings of the reference energy.

In the 'energy' timelap, the work piece material goes from room temperature to temperatures related to the liquid phase. Only very limited evaporation takes place during this time, which makes the surface temperature measurement reliable because of the absence of additional plume emission. Also the heat distribution is in a very primary state, almost entirely dominated by the properties of the top metal sheet. This limits the influence of the gap between the sheets to acceptable proportions, making a good differentiation between energy and gap parameters possible.

State of the art of existing weld monitoring systems.

The problem of the existing weld monitoring systems, such as the ProWatcher is that its signal behavior (which is taken during the weld and which uses radiation in the visual spectral range of typically 400 nm to 800 nm) depends extremely on both the energy setting and the gap setting so that no reliable energy-related signal can be measured, because it is difficult to extract information from the signal for distinction between these influences (*viz.* energy and gap). This problem does not exist for detection of the temperature. The difference between the energy settings E = 3,36 J and E = 5,13 J is about 40 % as can be seen in Figure

3. In the time range 7.5 ms to 9.5 ms (blue marked range) the temperature level is approximately constant and is therefore independent of the energy.

Overall thermal emission from the spot welding area, clean laser spot welding

As mentioned before, the surface temperature detection is quite reliable as long as the emission from the plume above the surface remains limited. Recent studies have indicated that the pollution of the welding area and the involved equipment (optics), can be decreased significantly by keeping the process conditions well under excessive evaporation levels. On one hand this leads to a dramatic decrease of the plume emission signal, but on the other hand improves the reliability of the surface temperature measurement significantly. Using process conditions like this opens the way the observe the actual evolving spot welding process through evaluation of the surface temperature signal. The changing heat transfer characteristics during the process can be recognized from the signal course, indicating the melt pool reaching the end barrier of the top sheet and the moment when actual fusion between top sheet material and bottom sheet material takes place. An indication about the gap size can be extracted from the time delay between reaching end barrier and moment of fusion. A certain amount of evaporation is necessary to create a local recoil pressure to force the molten top material onto the bottom part and start the fusion. This process can be supported by introducing a high energy level during a short period (spike). Once the fusion has started, it will continue without further need of recoil pressure. Figure 4 shows some surface temperature signals recorded during spot welding under low evaporation conditions with a spike for fusion support.

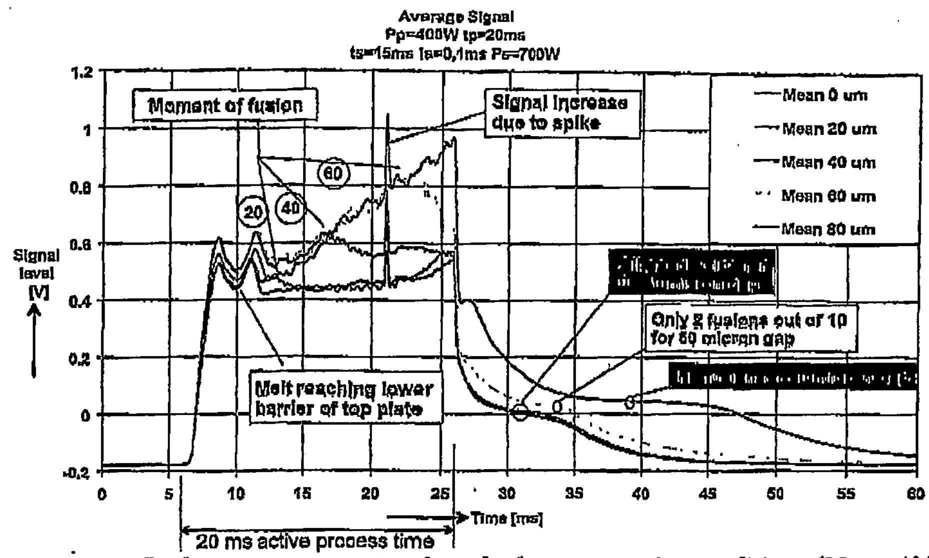

Figure 4: *Surface temperature signals under low evaporation conditions (20ms, 400W)*
Fusion supporting spike at 15 ms , 700 W during 0.1 ms
Serie of 10 spot weld experiments for each gap size

Once the melt pool reaches the bottom boundary of the top sheet, the initially spherical shaped melt pool boundary changes too circular (Temperature signal shows the first minimum). After this, the melt can only extend into the plane of the sheet, having a higher thermal resistance, leading to a temperature increase at the surface. Approximately 1-1.5 ms after the first minimum, the top spot size decreases while the bottom melt diameter still increases, indicating a momentary power decrease and/or absorption dip. This causes a second minimum in the temperature signal. After this the top and bottom melt size are about the same size and the temperature signal remains rather stable when the gap size is very small. When a certain gap is present, the temperature increases steadily after the second minimum. This continues until the moment that a fusing of top material with bottom material starts, and energy is being transferred to the bottom sheet, leading to a decrease of the surface temperature. With larger gap sizes, the temperature increases to higher levels. Figure 4 shows that gaps of 60 micron are not bridged before the spike on the laser power is introduced. For the shown experiments in figure 4, the spike was able to initiate fusing for 2 gaps out of 10 for the 60 micron experiments. In case the gap size increases to 80 microns, it becomes too large to be bridged with the used spike.

The idea is to use a predetermined spike power/time combination which is able to bridge a gap which is acceptable for the given geometry. This spike is to be introduced when the

temperature signal indicates that fusing has not started before a certain time. After this the temperature signal immediately indicates whether the spike action was successful or not. This information can be used as input for the automatic classification.

Results

Using the joint monitoring sensor as proposed here we obtain

for high plume emission processes:

- good detection of the weld energy during the initial process phase, independent of the gap between the metal parts.
- good joining detection in the cooling period after the actual welding process, independent of the energy.

for low evaporation level / clean welding processes:

- capability of tracking the process evolution and actively introducing a power spike for short period recoil pressure capable of bridging a preselected gap size.

CLAIMS:

1. Method of laser spot welding, the method comprising:

- heating of work piece parts until a preset temperature is reached;
- melting of the work piece parts under a substantially constant temperature until a preset amount of laser energy has been absorbed;
- cooling of the joined work piece parts.

2. Sensor for monitoring joints created by laser spot welding, characterized in that the sensor comprises a temperature sensor.